

Exelon Generation  
200 Exelon Way  
KSA3-N  
Kennett Square, PA 19348

Telephone 610.765.5661  
Fax 610.765.5545  
www.exeloncorp.com

Project No. 713

January 31, 2002

U.S. Nuclear Regulatory Commission  
Attn: Document Control Desk  
Washington, DC 20555

Subject: Submittal of Fuel Fabrication Quality Control Measures and Performance Monitoring Plans for the Pebble Bed Modular Reactor (PBMR) Fuel

At a meeting between Exelon Generation Company (EGC), LLC and the US Nuclear Regulatory Commission (NRC) on June 13, 2001 a presentation was made by EGC regarding attributes of the PBMR fuel design and qualification. Portions of this presentation were considered by us to be confidential (i.e., proprietary).

Attachment 1, "Fuel Fabrication Quality Control Measures and Performance Monitoring Plans for PBMR Fuel," is a narrative, which complements portions of the "PBMR Fuel Overview" presentation made on June 13, 2001. We consider portions of this document to be confidential (i.e., proprietary).

Portions of Attachment 1 are requested to be withheld from public disclosure on the grounds that these portions contain information in the nature of trade secrets and commercial or financial information that is confidential. We consider, however, that pre-application discussion of this information with NRC will be beneficial to the NRC's understanding of the PBMR fuel design, fabrication and qualification activities, and this type of discussion is consistent with the NRC's policy on Advanced Reactors, NUREG 1226 "Development and Utilization of the NRC Policy Statement on the Regulation of Advanced Nuclear Power Plants." This will allow the NRC to provide early input to us regarding attributes of these activities which are considered important to the NRC, such that these insights can be considered for inclusion in the PBMR fuel design and qualification process.

We have enclosed an application for withholding information from public disclosure pursuant to 10 CFR 2.790 (a) (4) regarding this information.

Attachment 1 contains the discussion materials, which includes areas considered by EGC to be confidential. Attachment 2 contains a non-proprietary version (i.e. proprietary portion intentionally deleted) of the discussion materials.

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We are in the process of re-evaluating the entire June 13, 2001 "PBMR Fuel Overview" slide presentation with regard to proprietary status (i.e., to determine if portions should now be re-classify as non-proprietary). Since the June 13, 2001 presentation slides contain more than the PBMR fuel quality control information provided in the attachments to this letter, we will discuss the proprietary status of the entire June 13, 2001 presentation slides in separate correspondence.

This information is being submitted under affirmation, and the required affidavit is enclosed.

If you have any questions concerning this matter, please do not hesitate to contact us.

Very truly yours,

A handwritten signature in black ink, appearing to read "Marilyn C. Kray". The signature is fluid and cursive, with the first name "Marilyn" and last name "Kray" clearly distinguishable.

Marilyn C. Kray  
Vice President, Special Projects

Enclosures: Affidavit  
Attachments

cc: Farouk Eltawila, Office of Nuclear Reactor Research  
James Lyons, Office of Nuclear Reactor Regulation  
John Flack, Office of Nuclear Reactor Research  
Amy Cabbage, Office of Nuclear Reactor Regulation  
Stuart Rubin, Office of Nuclear Reactor Research

Affidavit of Marilyn C. Kray

Commonwealth of Pennsylvania:

: ss.

County of Chester

:

Marilyn C. Kray being duly sworn, deposes and states as follows:

1. I am Vice President, Special Projects, Exelon Generation Company, L.L.C. (Exelon), and I am authorized to execute this affidavit in support of a request to withhold certain information, described in paragraph (2) below, from public disclosure and in accordance with Section 2.790(a)(4) of the Commission's regulations.
2. The information sought to be withheld is contained in the letter, M. C. Kray (Exelon Generation Company, L.L.C.) to the U. S. Nuclear Regulatory Commission Document Control Desk, Project No. 713.
3. The information which is sought to be withheld from public disclosure is proprietary information of Pebble Bed Modular Reactor (Pty) Limited, a Republic of South Africa corporation ("PBMR Co"), and has been provided to Exelon subject to an agreement that it will be treated as confidential and proprietary information and not be disclosed publicly. Exelon has contributed substantial funds for the development of the information and holds a beneficial ownership interest in PBMR Co.
4. In making this application for withholding of proprietary information, Exelon relies upon the exemption from disclosure set forth in the Freedom of Information Act ("FOIA"), 5 USC Sec. 552(b)(4), and the Trade Secrets Act, 18 USC Sec. 1905, and NRC regulations 10 CFR Section 9.17(a)(4) and Section 2.790(a)(4) for "trade secrets and commercial or financial information obtained from a person and privileged or confidential." The material for which exemption from disclosure is here sought is all "confidential commercial information," and some portions also qualify under the narrower definition of "trade secret," within the meanings assigned to those terms for purposes of FOIA Exemption 4 in, respectively, Critical Mass Energy Project v. Nuclear Regulatory Commission, 975F2d871 (DC Cir. 1992), and Public Citizen Health Research Group v. FDA, 704F2d1280 (DC Cir. 1983).
5. Some examples of categories of information which fit into the definition of proprietary information and which are applicable here are:
  - a) Information that discloses a process, method, or apparatus, including supporting data and analyses, where prevention of its use by the Company's competitors without license from Exelon Generation Company, L.L.C. constitutes a competitive economic advantage over other companies;

- b) Information which, if used by a competitor, would reduce his expenditure of resources or improve his competitive position in the performance of outages or the design, manufacture, shipment, installation, assurance of quality, or licensing of a similar product.
6. The information sought to be withheld is being submitted to the U. S. Nuclear Regulatory Commission ("NRC") in confidence. The information is of a sort customarily held in confidence by Exelon, and is in fact so held. Its initial designation as proprietary information, and the subsequent steps taken to prevent its unauthorized disclosure, are as set forth in (7) and (8) following. The information sought to be withheld has, to the best of my knowledge and belief, is not available in public sources. All disclosures to third parties including any required transmittals to NRC, have been made, or must be made, pursuant to regulatory provisions or proprietary agreements which provide for maintenance of the information in confidence.
  7. Initial approval of proprietary treatment of a document is made by the Vice President, Special Projects, the person most likely to be acquainted with the value and sensitivity of the information in relation to industry knowledge.
  8. The procedure for approval of external release of such a document typically requires review by a Vice President, Exelon Generation, or her/his designee, for technical content, competitive effect, and determination of the accuracy of the proprietary designation. Disclosures outside Exelon Generation Company, L.L.C. are limited to regulatory bodies, customers, and potential customers, and their agents, suppliers, and licensees, and others with a legitimate need for the information, and then only in accordance with appropriate regulatory provisions or proprietary agreements.
  9. The information identified in paragraph (2) is classified as proprietary because it contains fuel design information related to the Pebble Bed Modular Reactor (PBMR).
  10. Public disclosure of the information sought to be withheld is likely to cause substantial harm to Exelon's and others contributing to the PBMR Project competitive position and foreclose or reduce the availability of profit-making opportunities. The fuel design issues related to the PBMR provide commercial value to Exelon and its partners. The research, development, engineering, analytical, and NRC review costs comprise a substantial investment of time and money by Exelon and its partners.

Exelon's and its partners' competitive advantage will be lost if its competitors are able to use the design information.

The value of this information would be lost if the information were disclosed to the public. Making such information available to competitors without their having been required to undertake a similar expenditure of resources would unfairly provide competitors with a windfall, and deprive Exelon of the opportunity to exercise its competitive advantage to seek an adequate return on its large investment.

11. She has read the foregoing affidavit and the matters stated therein are true and correct to the best of her knowledge, information and belief.

Marilyn C. Kray  
Marilyn C. Kray

Subscribed and sworn to  
before me this 31<sup>st</sup> day  
of January 2002.

Staci L. Cooper  
Notary Public

Notarial Seal  
Staci L. Cooper, Notary Public  
Kennett Twp., Chester County  
My Commission Expires Sept. 20, 2004  
Member, Pennsylvania Association of Notaries

## **Attachment 2**

**--Nonproprietary Information --**

**"Fuel Fabrication Quality Control Measures and Performance Monitoring Plans  
for PBMR Fuel" – Nonproprietary Version**

**January 31, 2002**

**14 Pages**

NONPROPRIETARY

**FUEL FABRICATION QUALITY CONTROL MEASURES AND  
PERFORMANCE MONITORING PLANS FOR PBMR FUEL**

**January 31, 2002**

**NONPROPRIETARY VERSION**

## **1. INTRODUCTION**

A fundamental aspect of the PBMR safety case is the robustness of the PBMR TRISO coated particle fuel. The production of high quality fuel is essential for ensuring the retention of fission products during both normal operating and potential accident conditions. A set of well defined manufacturing process and quality controls is critical to the consistent production of high quality fuel. This paper summarizes the manufacturing process for PBMR fuel, including the key fuel specifications and the quality control process. The specific parameters measured as part of the quality control process are discussed, along with methods used to measure them.

Another aspect of PBMR fuel quality is the monitoring of the fuel performance. The monitoring plan for fuel performance includes the methods for monitoring the core operating conditions, the detection of failed fuel in the reactor, and the determination of fuel burn -up levels.



## 2. FUEL FABRICATION

### 2.1 Overview of TRISO Fuel Manufacturing Process

TRISO coated fuel elements consist of coated particles embedded in cold pressed graphite matrix material. The coated particles consist of spherical  $\text{UO}_2$  kernels surrounded by four concentric layers. The first layer surrounding the kernel is a porous pyrocarbon layer, known as the buffer layer. This is followed by an inner high-density pyrocarbon layer, a silicon carbide (SiC) layer, and an outer high-density pyrocarbon layer. The layers are deposited sequentially by dissociation of gaseous chemical compounds in a continuous process in a fluidized bed. The overall fuel manufacturing process is shown schematically in *Figure 1*.

The spherical fuel kernel consists of stoichiometric uranium dioxide ( $\text{UO}_2$ ). The basic manufacturing steps for the kernel are as follows.  $\text{U}_3\text{O}_8$  powder is dissolved in nitric acid to form uranyl nitrate. The solution is neutralized with ammonia and allowed to flow through an oscillating nozzle to produce droplets. As the droplets fall through a gaseous ammonia atmosphere, the spherical outer surface of the droplet gels. The particles fall into an aqueous ammonia solution where they solidify into ammonium diuranate. They are then aged and washed to remove ammonium nitrate and organic additives, dried, and calcined. This is followed by reduction to  $\text{UO}_2$  in hydrogen and sintering to produce the final kernels. The kernels are then sieved to remove over- and under-sized particles, and are then sorted on vibrating plates to remove odd-shaped particles.

The first layer in contact with the kernel is known as the buffer layer, and it is deposited at a temperature of 1200 °C from acetylene ( $\text{C}_2\text{H}_2$ ). The other conditions in the fluidized bed are arranged to keep the density of this layer below the maximum allowed value of 1.05 g/cm<sup>3</sup>, which is about 46% of the theoretical density of pyrocarbon (2.26 g/cm<sup>3</sup>).

The inner high-density, isotropic layer of pyrolytic carbon is also referred to as the Inner Low Temperature Isotropic (ILTI) pyrocarbon layer. It is deposited from a mixture of  $\text{C}_2\text{H}_2$  and propylene ( $\text{C}_3\text{H}_6$ ) at a temperature of 1300 °C in a fluidized bed, and has an average density of 1.90 g/cm<sup>3</sup>. This layer forms the first barrier against the pressure exerted by fission products within the fuel kernel, thereby reducing the pressure on the next layer (SiC). During irradiation, this layer shrinks at first, and then expands again as higher fast neutron dose levels are reached. The interaction between the inner and outer high density pyrocarbon layers and the SiC layer during irradiation plays an important part in keeping the SiC layer under compressive stress as long as possible.

The SiC layer is deposited from methyltrichlorsilane ( $\text{CH}_3\text{SiCl}_3$ ) at 1500 °C, achieving a minimum density of 3.18 g/cm<sup>3</sup> (nearly theoretical density). At high temperatures, the ILTI layer partially loses its ability to contain caesium and strontium. The purpose of the SiC layer is to prevent the release of these fission products into the graphite matrix and eventually into the reactor coolant stream. The SiC acts as the principal pressure barrier in the coated particle. The coated particle structure results in the SiC layer being kept under compression as long as possible by its interaction with the inner and outer pyrocarbon layers.

The Outer Low Temperature Isotropic (OLTI) pyrolytic carbon layer is deposited in exactly the same way as the ILTI layer. The function of this layer is to protect the SiC layer against damage during the fuel sphere pressing stage of the fuel manufacturing process. It also provides a pre-stress on the outside of the SiC layer, due its interaction with the ILTI layer under fast neutron irradiation during the fuel lifetime in the reactor core, thereby reducing the tensile stress in the SiC layer.

The coated particles are over-coated and embedded in graphite matrix material consisting of a mixture of natural graphite and electrographite, together with a phenolic resin which acts as a binder material. The function of the graphite matrix is to contain and protect the coated particles from mechanical damage and to provide a heat conduction path between the coated particles and the reactor coolant. PBMR fuel elements are pressed in two steps. Before the coated particles are mixed into the matrix material for pressing, a coating of matrix material is applied to the outer surface of each coated particle in a rotating drum. This coating is known as the 'overcoat', and its purpose is to prevent coated particles from coming into contact with each other, and thereby damaging their coatings during pressing of the fuel elements. In the first step, coated particles and matrix material are mixed and pressed to form a fuel containing inner sphere. Fuel particles are distributed as evenly as possible in the inner fuel -containing zone (diameter of 50 mm) to prevent the development of hot spots in a fuel element. In the second step, matrix material is added to the mould and pressed to form a 5 mm thick fuel free region around the fuel -containing zone. The purpose of this zone is to protect the inner zone from mechanical and chemical damage during fuel handling and operation. The spheres are machined, carbonised at 800 °C, and then receive a final heat treatment at a temperature of 1950 °C.

## **2.2 Fuel Specifications**

The specification for the manufacture of fuel for the PBMR will be based on the NUKEM specification used to manufacture the AVR 21 -2 reload batch for the AVR reactor in Germany. The process used for this batch was the state of the art at the time that the German program ended;

fuel produced using this process demonstrated the lowest free uranium release fraction when subjected to a burn leach test. The key design specifications are shown in **Table 1**. The specifications in **Table 1** are identical to the AVR 21-2 reference batch process with the exception of the anisotropy specification for the ILTI and OLTl layers. The NUKEM specification for this value was 1.10, while the PBMR fuel will use the more restrictive 1.08 value shown in the table.

The direct materials used to manufacture the spheres include both natural and electrographite powders, as well as phenolic resin. These direct materials will be compliant with the same specification used for the reference batch process.

**[Proprietary information related to specific material suppliers has been removed]**

Material specifications for the indirect materials used in manufacturing the fuel, such as the process gases used to produce the coatings, have been established to ensure sufficient purity.

### 2.3 Quality Control Process

As indicated in **Figure 1**, there are several quality check points in the manufacturing process. The first check is performed as needed on the incoming feed materials. The checks that may be performed on the feed material are primarily chemical tests for impurities and chemical makeup. As an example, the specific characteristics that may be measured as part of this quality check are shown in **Table 2**.

The next quality check is performed on the uncoated  $\text{UO}_2$  kernels following completion of sintering, sieving and sorting.

**Table 3** lists the specific quality attributes which are measured as part of this quality step. A check performed at this stage is the measurement of the sphericity of the kernels. Highly spherical kernels are required to ensure that stress peaks do not occur in the coatings during operation. This check is performed, and the kernel diameters are measured, by the use of an optical particle size analyser. Kernel batches which fail to meet any of the quality specifications are recycled; the uranium is recovered and fed back as feed material. Kernel batches which pass all the criteria are released for coating.

Quality checks are performed at several points during the coating process. Samples are removed from the batch at each stage of the coating process, and specific attributes are measured. **Table 4** lists all of the quality attributes measured for the coated particles. Typical measurement methods to determine the thickness and density of each coating layer include the following:

- The buffer layer thickness is determined by use of metallography and an image analyser. A particle size analyser and weigh scale is used to measure the buffer layer density.
- The thickness of the ILTI pyrocarbon layer is also measured using metallography and an image analyser; the density of this layer is measured by use of a gradient column.
- The thickness of both the SiC and OLTl pyrocarbon layers is determined by radiography.
- The densities of each of these layers is measured by use of a gradient column.

Coated particle batches which fail to meet one or more of the quality characteristics in **Table 4** are recycled. The coatings are removed by chemical and mechanical processes and the recovered uranium is fed back as feed material.

The final quality check is performed on the final pressed fuel spheres after the completion of heat treatment.

**Table 5** lists the quality characteristics measured as part of this final quality check. These checks primarily involve chemical tests for impurity content, and mechanical tests for physical integrity. Spheres which fail any of the criteria are recycled and the uranium is recovered.

### **3. FUEL PERFORMANCE**

#### **3.1 Core Condition Monitoring**

Another aspect of ensuring fuel integrity is the accurate determination of core operating conditions. The PBMR is provided with instrumentation for monitoring the critical parameters necessary for determining the core operating conditions.

Neutron flux measurements are accomplished by the use of ex-core detectors which are situated outside the reactor pressure vessel. These detectors are calibrated against the calorimetric heat balance. In addition, the demonstration plant will include sacrificial in-core flux detectors situated in the graphite core structure.

The helium coolant temperature is measured at both the vessel inlet and outlet pipe locations. For the demonstration plant, thermocouples will be provided internal to the vessel to confirm the expected temperature conditions. Coolant pressure will be measured at the vessel inlet pipe; the differential pressure between the inlet and outlet pipes will also be measured. The coolant flow rate will be measured at the inlet pipe location.

The coolant condition will be monitored by taking samples in the Helium Purification System (HPS). A gas chromatograph will be used to measure  $H_2$ ,  $CH_4$ ,  $CO$ ,  $CO_2$ ,  $N_2$ ,  $Xe$ , and  $Kr$  levels. A moisture analyser will be used to measure water vapor content of the coolant. A gamma spectroscopy will be used to determine the gamma activity in the coolant.

Fuel integrity is directly monitored by measurement of the noble gas fission product levels in the coolant. The noble fission gas activity in the circulating PBMR coolant will be measured continuously during reactor operation, to detect any undue increase in the failure fraction of coated particles in the operating reactor core. This will enable early remedial measures to be taken in any case where the failure fraction in the reactor core shows signs of increasing beyond expected levels.

#### **3.2 Fuel Burn-up Determination**

An accurate determination of the fuel burn-up level is critical to ensuring reliable operation of the fuel. The burn up measurement system distinguishes between irradiated graphite and irradiated fuel, as well as between used fuel and spent fuel. The system is a Germanium detector based system that determines sphere identity and burn up from its radiated gamma spectrum. Within the first 2 seconds of measurement, it determines whether the sphere is graphite or fuel. In the next 3

seconds of measurement it determines whether or not the fuel sphere is used fuel. Within the next 5 seconds of measurement the system determines whether the fuel sphere is acceptable for another pass through the reactor, or whether it must be discharged. The maximum measurement time per sphere is 10 seconds. The Burn-up Measurement System (BUMS) determines burn-up within an accuracy of  $\pm 4\%$ .

Major components of the system are the collimator, Germanium detector, amplifier, signal processor, and computer assembly. An electromechanical cooler cools the Germanium detector. The system measures the Cs-137 activity in the fuel sphere using gamma spectrometry. The 661.6 keV gamma is used as the reference for counting. The resolution of the Germanium detector is 1.6 keV, which is fine enough to minimise gamma count contributions from potentially interfering gammas from other isotopes (Nb-97, Ce-143, and I -132).

The system performs extensive self-diagnostics, and also includes two radioactive sources. A low activity Ba-133 check source is provided, and is measured with each gamma spectrum. The anticipated spectrum from the known check source is used to verify operability of the burn-up measurement system every time a measurement is performed. The second source is a Cs-137 calibration source that is mechanically operated and normally shielded from the system. It is only used for calibration and normalization measurements.

Table 1: DESIGN SPECIFICATION FOR PBM R FUEL ELEMENT

Fuel Element Component	Specified Characteristic	Specification
Kernels	Stoichiometry	[Proprietary information deleted]
	Diameter	[Proprietary information deleted]
	Sphericity	The ratio between the maximum diameter $d_m$ and the minimum diameter $d_m$ shall fulfil the following condition: [Proprietary information deleted]
	Density	The average density $\bar{x} \geq$ [Proprietary information deleted]
Coated Particles	Thickness	Buffer Layer (PyC): $\bar{x} = 95 \mu\text{m}$ Inner Pyrocarbon Layer (PyC): $\bar{x} = 40 \mu\text{m}$ Silicon Carbide Layer (SiC): $\bar{x} = 35 \mu\text{m}$ Outer Pyrocarbon Layer (PyC): $\bar{x} = 40 \mu\text{m}$
	Density	<i>The average layer densities shall be as follows:</i> Buffer Layer (PyC): $\bar{x} \leq 1.05 \text{ g/cm}^3$ Inner Pyrocarbon Layer (PyC): $\bar{x} = 1.90 \text{ g/cm}^3$ Silicon Carbide Layer (SiC): $\bar{x} \geq 3.18 \text{ g/cm}^3$ Outer Pyrocarbon Layer (PyC): $\bar{x} = 1.90 \text{ g/cm}^3$
	Anisotropy for Layers 2 and 4	<i>The average layer anisotropy shall be as follows:</i> Layer 2 (ILTI Layer): $\bar{x} \leq$ [Proprietary information deleted] Layer 4 (OLTI Layer): $\bar{x} \leq$ [Proprietary information deleted]
Fuel Elements	Uranium loading per sphere	9 grams
	Particles per fuel sphere	[Proprietary information deleted]
	Boron equivalent	[Proprietary information deleted]
	Ash content	[Proprietary information deleted]
	Lithium content	[Proprietary information deleted]
	Free uranium fraction	[Proprietary information deleted]
	Carbon content	[Proprietary information deleted]
	Diameter	[Proprietary information deleted]
	Thickness of fuel free zone	[Proprietary information deleted]
	Coated particles in fuel free zone	[Proprietary information deleted]
	Drop strength	[Proprietary information deleted]
	Crush strength	[Proprietary information deleted]
	Abrasion	[Proprietary information deleted]
	Corrosion rate	[Proprietary information deleted]
	Thermal conductivity	[Proprietary information deleted]
	Thermal expansion anisotropy	[Proprietary information deleted]



**Table 2: QC MEASURED CHARACTERISITICS -  $U_3O_8$** 

Characteristic
Uranium enrichment
Isotopic content
Impurities
Stoichiometry
Uranium content
Equivalent boron content
Moisture content
Particle size

**Table 3: QC MEASURED CHARACTERISITICS -  $UO_2$  KERNELS**

Characteristic
Diameter
Density
Sphericity
Equivalent boron content
Stoichiometry

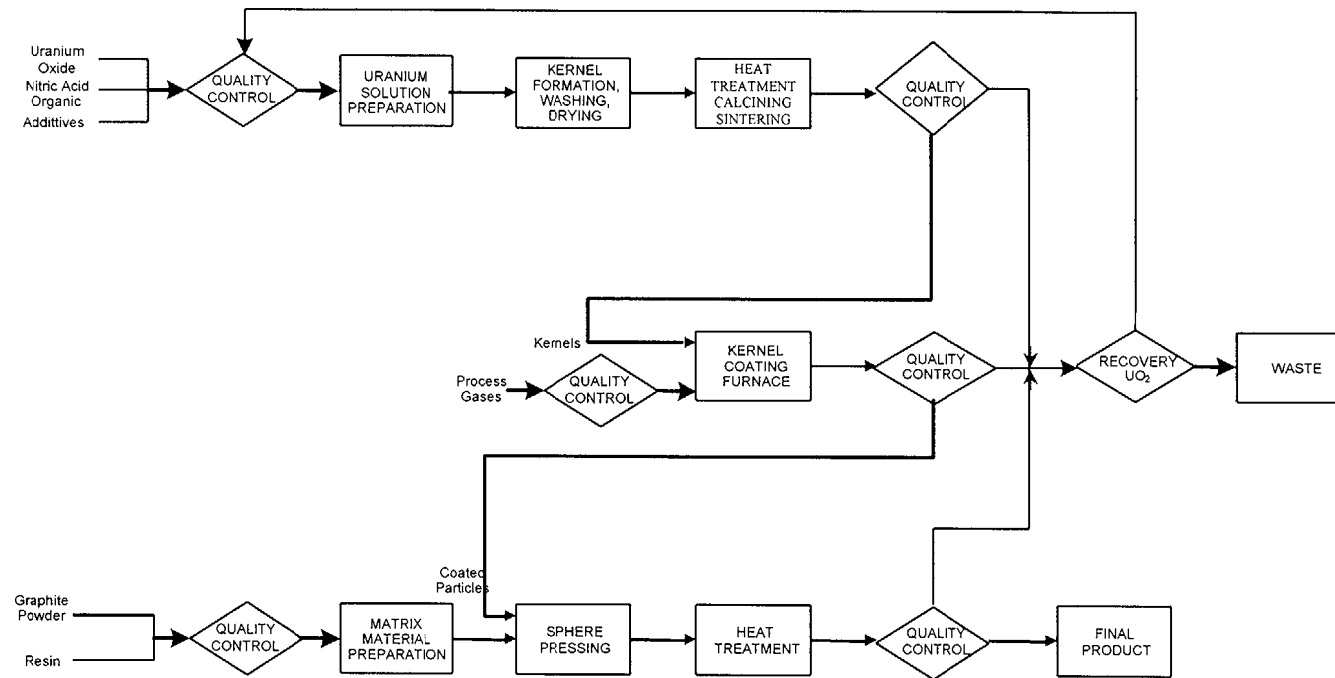
**Table 4: QC MEASURED CHARACTERISITICS - COATED PARTICLES**

Characteristic
Buffer layer thickness
Buffer layer density
ILTI layer thickness
ILTI layer density
SiC layer thickness
SiC layer density
OLTI layer thickness
OLTI layer density
Anisotropy of ILTI and OLTI layers
Unconfined uranium (burn leach)
Isotopic content
Uranium content
Uranium enrichment

**Table 5: QC MEASURED CHARACTERISTICS – FUEL SPHERES**

Characteristic
Uranium enrichment (calculated from coated particle results)
Uranium content (calculated from coated particle results)
Equivalent boron content of matrix material (plus kernels)
Ash content of matrix material
Lithium content of matrix material
Unconfined uranium (burn leach)
Carbon content
Sphere diameter
Fuel free zone shell thickness
Surface defects
Drop strength
Crushing strength
Thermal conductivity of matrix material
Anisotropy of matrix material
Abrasion of matrix material
Corrosion of matrix material
Density of matrix material

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NOTE: Additional internal QC checks are not shown on this schematic.

**Figure 1: FUEL MANUFACTURING PROCESS**